THE EFFECT OF PERFORMANCE STAGES ON SUBWOOFER POLAR AND FREQUENCY RESPONSES

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1 INTRODUCTION

Advancements in live sound reinforcement over the past few decades have allowed for increasingly precise sound field control at large-scale live events. This includes the ability to direct low-frequency energy (typically below 120 Hz) towards the audience and away from the stage in order to limit noise exposure for musicians and production staff.

Central to low-frequency directionality is the seminal work of Harry Olsen [1], describing how techniques used to control microphone polar patterns can be applied to loudspeakers (gradient loudspeakers). This has been adopted by a number of loudspeaker manufacturers in order to develop directional subwoofers (both single units and arrays) [2,3,4]. The single-unit variety typically has two or more drive units which are fed separate signals in order to create the desired coverage pattern [2,4]. Alternatively, users can configure two or more omnidirectional units as an array, using signal processing to achieve similar results (although this approach will result in an inconsistent polar response due to the frequency-independent delay applied to the system) [3,5].

Regardless of the particular approach utilized to achieve low-frequency directionality at live events, systems should be capable of keeping low-frequency energy on stage at comfortable levels while achieving the desired energy across the audience.

It was noted in 2010 that a performance stage can negate the directionality gained from these techniques [5]. When subwoofer systems are tested in isolation they produce their expected polar response. What's routinely overlooked, though, is that a performance stage can severely distort polar and frequency responses, where in extreme scenarios radiation directivity is completely lost and the frequency response is perceptibly colored.

This issue was analyzed using bespoke finite-difference time-domain (FDTD) acoustic modelling software in the 2010 paper [5,6]. Three configurations were examined using two spaced cardioid subwoofers: (1) under the stage, (2) on the stage corners and (3) just in front of the stage. The simulations were conducted first without the stage included in the model (which is in line with most commercially available system design software) and then with the stage included in the model.

In the initial investigation, configurations were tested only using a 60 Hz pure tone and the data wasn't thoroughly analyzed, since this wasn't the focus of the paper, but rather an interesting observation. What the results indicate, though, is that when a stage is included in a model, the low-frequency directionality gained via cardioid subwoofers is almost completely negated when the subwoofers are placed directly below the stage (Figure 1). A similar issue occurs when the subwoofers are placed on the stage, although stage levels are naturally increased with this configuration due to the closer proximity to the performance area (Figure 2).

When the subwoofers are moved in front of the stage (by one meter in this instance), directionality is maintained when the stage is introduced to the model (Figure 3). This finding gave a strong early indication that subwoofers should be placed just in front of the stage to ensure directionality is maintained, an approach which was adopted as standard practice by Gand Concert Sound, who were contributors to the research in the 2010 paper.

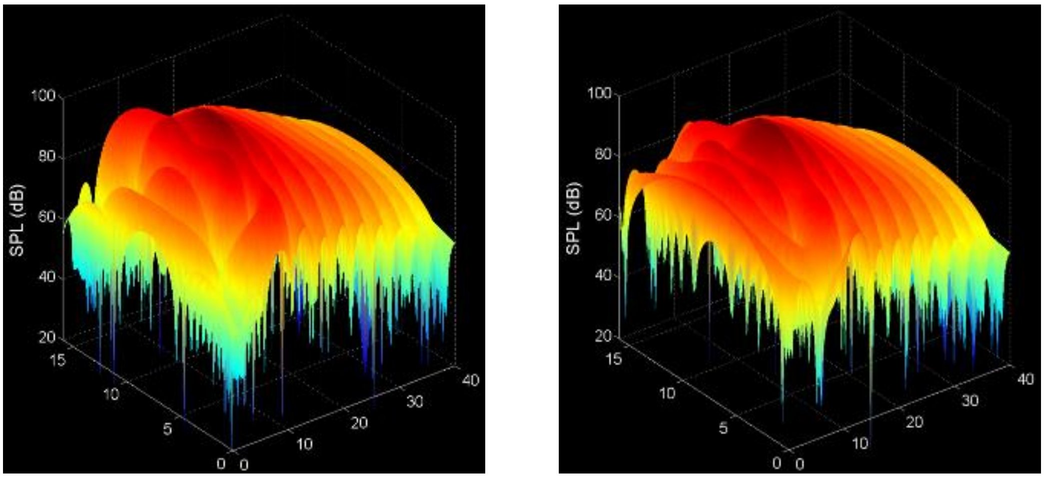


Figure 1 Sound pressure level distribution from two spaced subwoofers located directly underneath a stage using a 60 Hz pure tone source signal with and without a stage included in the model (right and left plots, respectively) (reproduced from the 2010 paper [5])

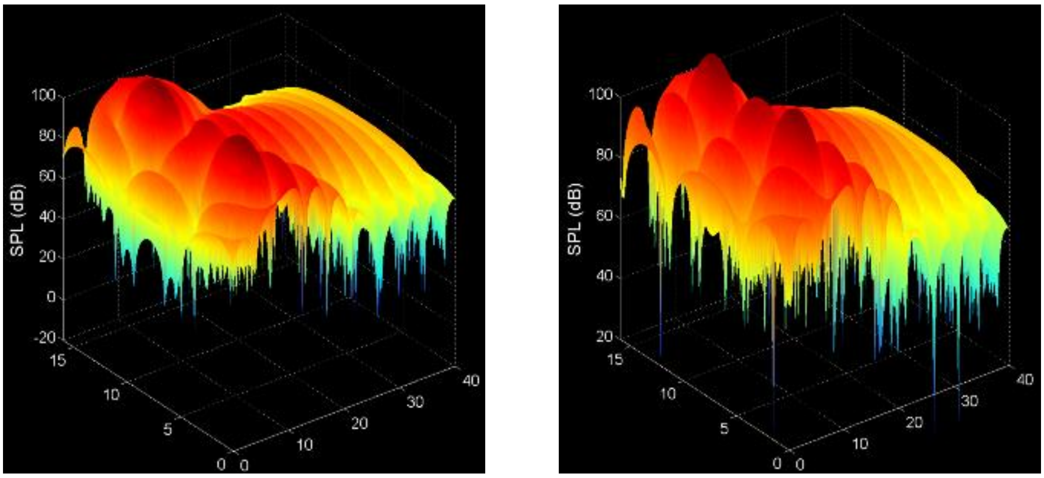


Figure 2 Sound pressure level distribution from two spaced subwoofers located on the two front stage corners using a 60 Hz pure tone source signal with and without a stage included in the model (right and left plots, respectively) (reproduced from the 2010 paper [5])

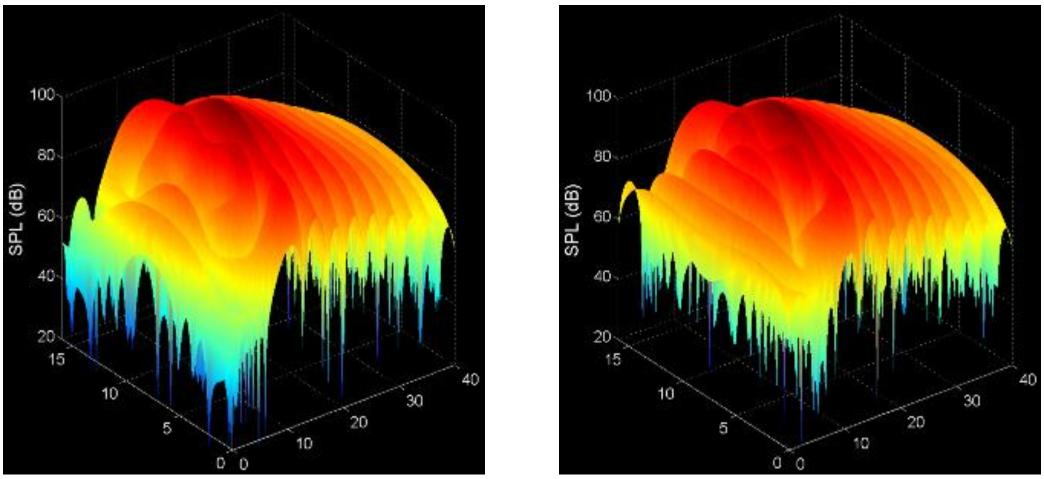


Figure 3 Sound pressure level distribution from two spaced subwoofers located one meter in front of the stage using a 60 Hz pure tone source signal with and without a stage included in the model (right and left plots, respectively) (reproduced from the 2010 paper [5])

The findings from the 2010 paper raise a clear need for further investigation. The research presented in this paper serves as a beginning to this through practical experiments to verify that the modeling performed in 2010 was accurate and to examine the phenomenon across a wide frequency range. This work is an expansion of the research carried out by one of the authors in 2015/16 [7]. The experimental configuration is described in detail in Section 2, followed by a full presentation of results with detailed analysis and discussion in Section 3. The work is concluded in Section 4, where an agenda for necessary further research is proposed.

2 EXPERIMENTAL CONFIGURATION

The experiment was conducted in a non-anechoic space (dimensions 11.6 m x 10.6 m x 9.1 m) since a large enough anechoic environment wasn't readily accessible at the time of testing. While not ideal for precise measurements, this environment is roughly representative of a small concert venue, which lends to the practical nature of this research.

To directly examine how polar response is affected by stage proximity, a two meter radius circle of measurement locations was laid out with one point every ten degrees, giving 36 measurement locations in total. The center of the circle was set as the front edge of the (eventual) stage location. Measurement distance was dictated by the dimensions and the content of the test space.

Three subwoofer locations were investigated: (1) directly under the stage (0.5 m behind the front stage edge), (2) on top of the stage (0.2 m behind the front stage edge) and (3) in front of the stage (0.85 m in front of the front stage edge). These locations allowed for a direct comparison to the 2010 paper [5].

A d&b audiotechnik Y subwoofer [8] was chosen for the tests, driven by a d&b audiotechnik D20 power amplifier [9]. The Y subwoofer manual states that the unit will achieve a cardioid dispersion pattern in its passband (Figure 4), provided that there is a minimum distance of 60 cm between adjacent cabinets or between a single unit and a side wall. The manual states that rear distance isn't an issue, as the wheels permanently mounted to the subwoofer ensure a minimum distance is maintained [8]. The published frequency response of the Y subwoofer is reproduced in Figure 4. The subwoofer was operated in 100 Hz mode for this experiment, resulting in a passband of 39 – 110 Hz, as opposed to the standard mode with a 39 – 140 Hz passband [8].

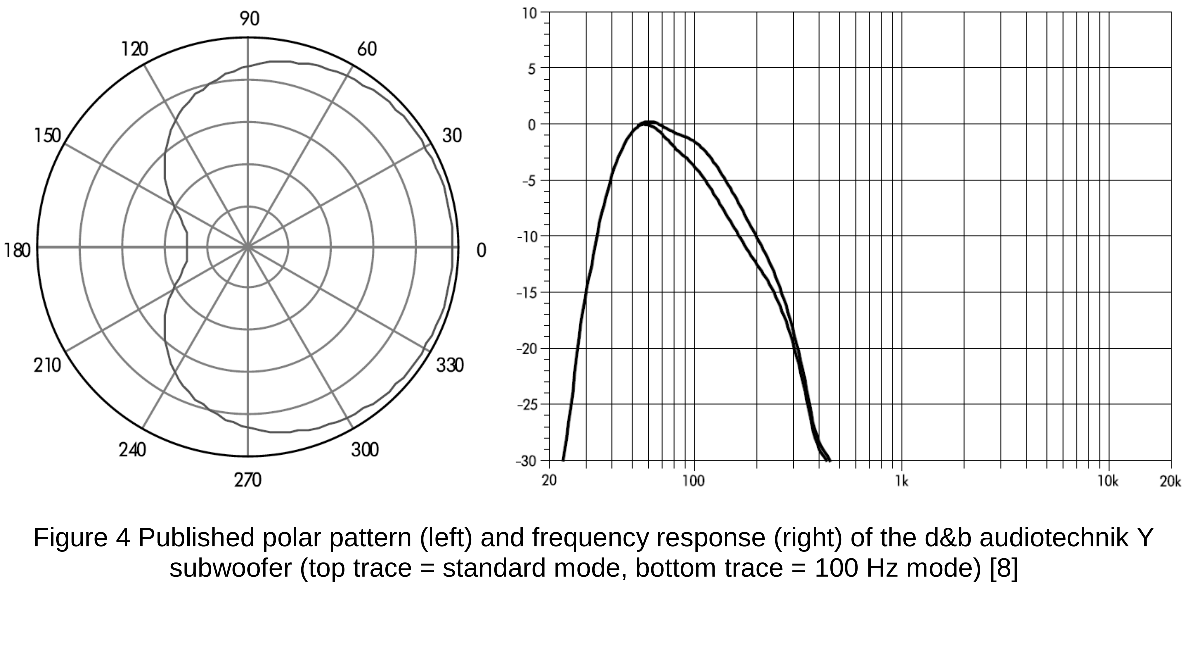


Figure 4 Published polar pattern (left) and frequency response (right) of the d&b audiotechnik Y subwoofer (top trace = standard mode, bottom trace = 100 Hz mode) [8]

Before introducing a stage into the experimental configuration, the subwoofer was measured on its own in the test space to create baseline polar and frequency response measurements for all proceeding measurements to use as a reference. All measurements were taken using CLIO Audiomatica FW10 hardware and software [10] with an MLS as the source signal. The measurement microphone was placed 1 cm from the floor to avoid unwanted low-frequency comb filtering from the floor reflection. The resulting polar responses (examined at 40 Hz, 80 Hz and 120 Hz) and frequency responses (examined on axis and 180° off axis) are shown in Figure 5.

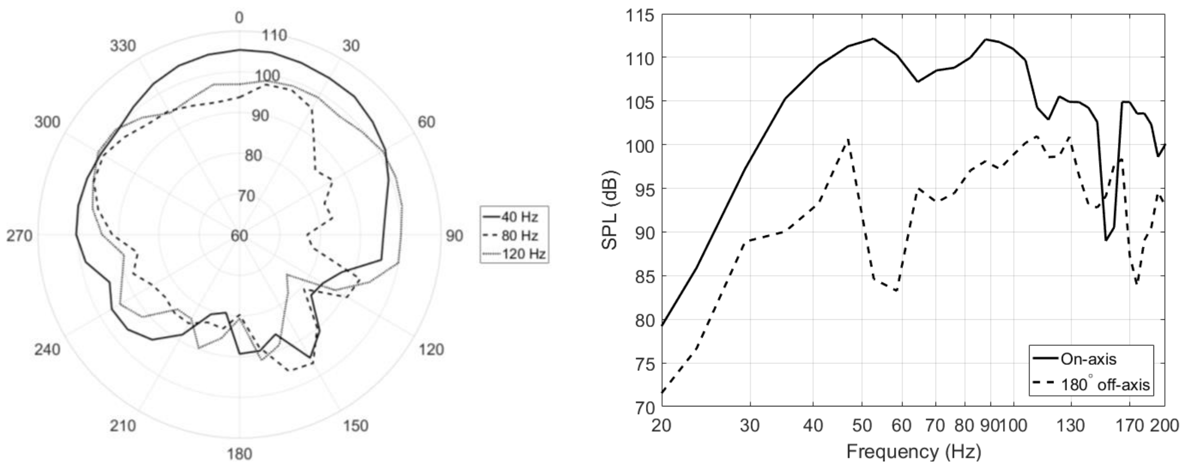


Figure 5 Measured polar (left) and frequency response (right) of the d&b audiotechnik Y subwoofer in a non-anechoic environment with no stage present

Bearing in mind that the equipment stored around the test space was asymmetrically placed, the measured polar responses achieve close to the expected cardioid pattern in the subwoofer passband. Front-to-back rejection values of 16.11 dB, 14.06 dB and 16.35 dB were recorded at 40 Hz, 80 Hz and 120 Hz, respectively, which is in agreement with the cardioid pattern shown in Figure 4 (assuming 5 dB increments), predicting around 17 dB front-to-back rejection.

The measured on-axis frequency response also agrees with the published response. The sound pressure level begins to fall in the measured data around 40 Hz and drops by approximately 30 dB towards 20 Hz, which agrees with the published data. The high-frequency roll-off appears to begin around 55 Hz, which is closely in line with expectations, but then rises again around 80 – 100 Hz before falling off again. This additional boost is likely due to room effects, leading to the conclusion that the subwoofer is performing as expected.

2.1 Small stage configuration

To commence investigating the impact of stage proximity on a directional subwoofer's polar and frequency responses, a single piece of stage deck was introduced into the test configuration (Figure 6). The piece of staging was of the industry-standard size of 8' x 4' (2.44 m x 1.22 m) and was set up with a height of 0.62 m.

The purpose of this configuration was to examine the impact a single piece of stage deck could have on a subwoofer. Could the relatively small dimensions of the stage with respect to the passband wavelength range result in no measureable impact or will the added obstacle significantly distort the polar and frequency responses? This serves as a good first step towards a better understanding of the stage proximity issue.

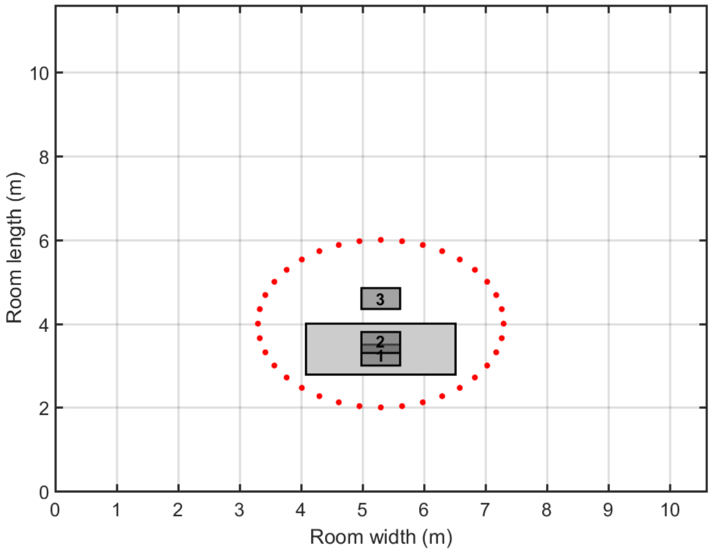


Figure 6 Small stage experimental configuration. Red dots indicate measurement locations. Small numbered rectangles indicate source locations (1 – under stage, 2 – on stage, 3 – in front of stage). Large unnumbered rectangles indicate pieces of stage deck.

2.2 Large stage configuration

Once the effects of a single piece of stage deck were investigated the next step required was to expand the stage so that it was of a more typical size found at live events. In this case, eight additional pieces of stage deck were bolted together into a 3 x 3 grid to form a 7.31 m x 3.65 m stage (Figure 7). The large stage was restricted to a height of 0.52 m due to the available stage legs. This meant that the d&b Y subwoofer couldn't fit underneath the stage. Due to this, the results for the under stage subwoofer position were modelled using FDTD software [6] to give an approximate representation of the stage effects on the system. While this is still a relatively small stage when compared to a large-scale event, it is sufficient to give a reasonable idea of the impact stage proximity has on subwoofer polar and frequency responses.

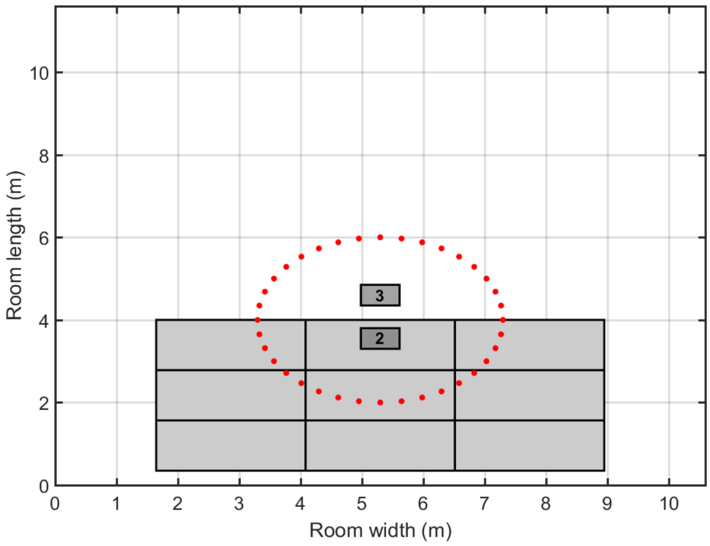


Figure 7 Large stage experimental configuration. Red dots indicate measurement locations. Small numbered rectangles indicate source locations (2 – on stage, 3 – in front of stage). Large unnumbered rectangles indicate pieces of stage deck.

3 RESULTS AND DISCUSSION

With all measurements complete, the results could be analyzed for insights into the practical implications of stage proximity on subwoofer responses at live events.

3.1 Small stage configuration

As with the measurements without a stage present, the three source placements can be examined in terms of polar response at 40, 80 and 120 Hz and frequency response. Polar responses for each of the three subwoofer locations are given along with the frequency responses on-axis and 180° off-axis in Figures 7 – 9. The reference frequency responses with no stage present are plotted in red to allow for direct comparisons.

Upon inspecting the on-axis audience frequency response for each subwoofer location, it can be clearly seen that the stage has minimal effect on the frequency response in the audience (at least front and center – off-axis audience locations will be examined later). There are, however, clear differences in the stage responses directly behind the subwoofer. Both the under stage and on stage location frequency responses show a front-to-back rejection reduction at 55 Hz around 15 dB. This is significant and means that in this frequency range the cardioid nature of the subwoofer is severely compromised. Furthermore, the under stage placement shows continued loss of directionality above the 55 Hz range, giving early indication that this location is particularly poor for the maintenance of the cardioid polar response.

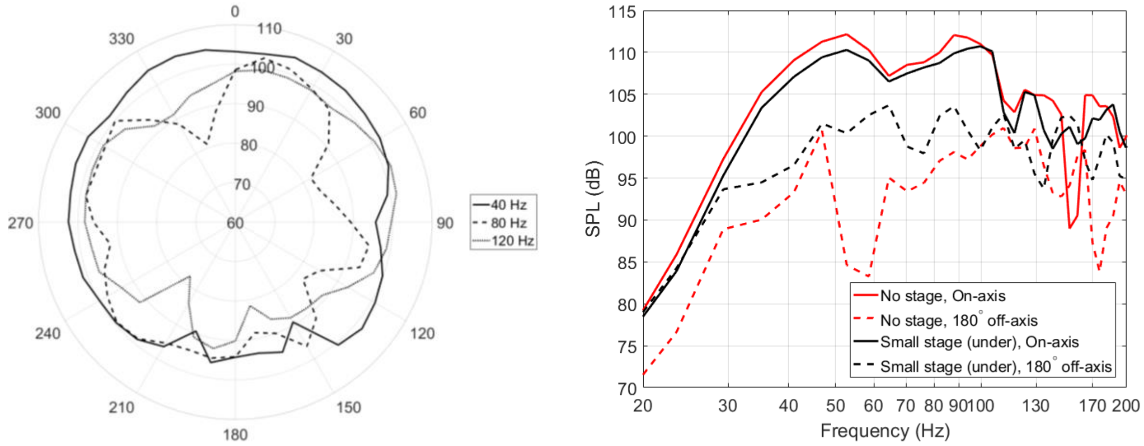


Figure 7 Measured polar responses (left) and frequency responses (right) of the d&b audiotechnik Y subwoofer in a non-anechoic environment, placed underneath a small stage

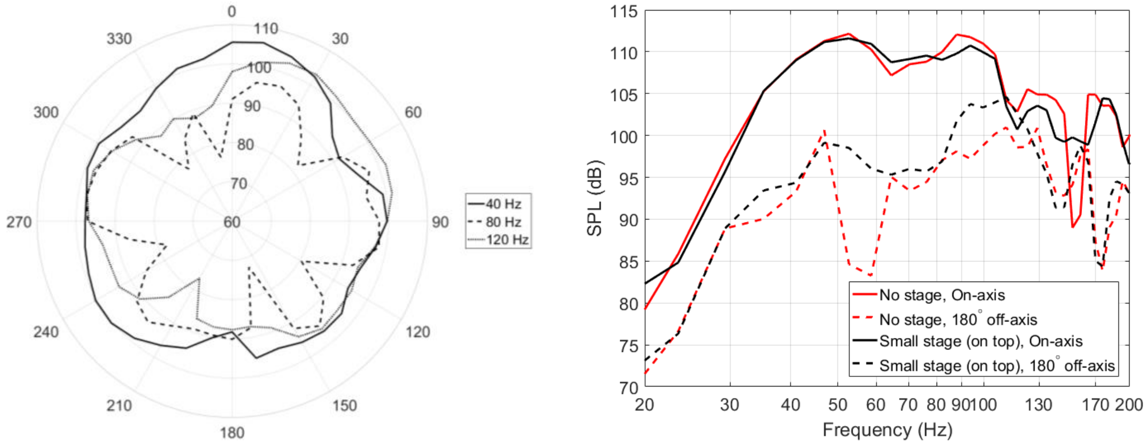


Figure 8 Measured polar responses (left) and frequency responses (right) of the d&b audiotechnik Y subwoofer in a non-anechoic environment, placed on top of a small stage

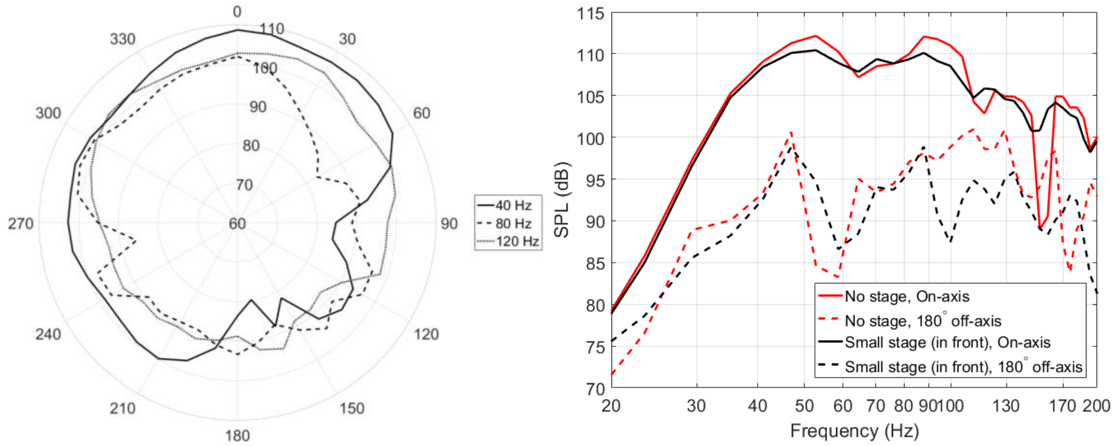


Figure 9 Measured polar responses (left) and frequency responses (right) of the d&b audiotechnik Y subwoofer in a non-anechoic environment, just in front of a small stage

When inspecting the in front of stage subwoofer location, on the other hand, it can be seen that the stage response follows the reference response quite closely and actually surpasses the reference response rejection above 90 Hz by around 10 dB. These findings strengthen the argument for subwoofers to be placed in front of the stage.

It's important to examine the system's behavior at all locations and not just directly in front and behind a subwoofer. To do this in a reasonable manner, the measurement locations were clustered in an audience group and a stage group. Since it's atypical for audience members or performers to be located at the very edge of either side of the stage front, the six measurement points in this region (representing ±20° off the front stage edge) were omitted from either group. The grouped measurements were averaged to give an overall idea of system behavior in the audience and on stage. The resulting frequency responses for the small stage configurations were subtracted from the stage-less reference configuration to arrive at a set of responses describing each configuration's deviation from reference (Figure 10).

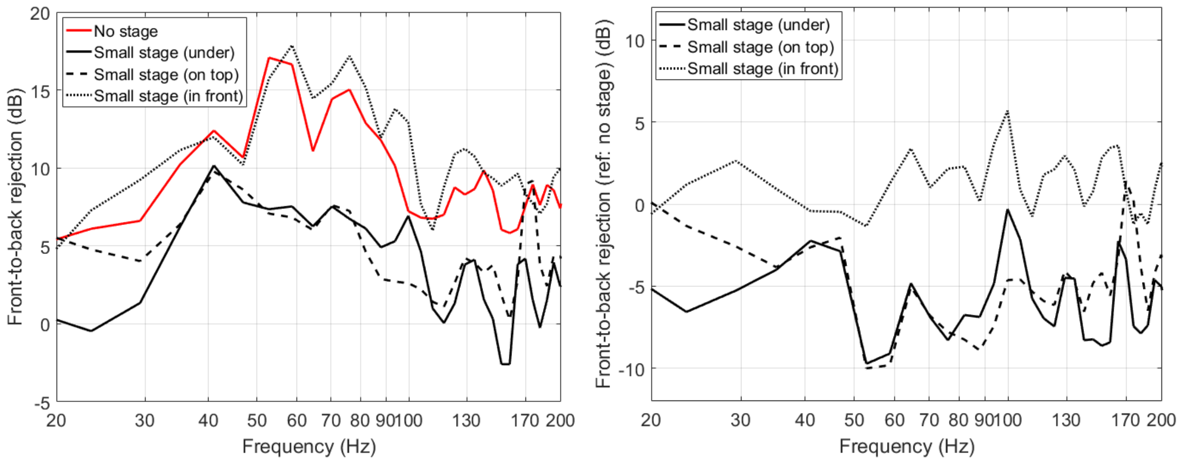


Figure 10 Comparision of front-to-back rejection for each of the subwoofer locations (left = direct comparsion to stage-less configuation, right = deviation from the stage-less configuration)

This analysis provides conclusive evidence that for the small stage experimental configuration placing the subwoofer in front of the stage is the superior option since this placement matches or exceeds the front-to-back rejection of the subwoofer on its own at nearly all frequencies. The under and on stage placements show significant reduction in the stage rejection, especially in the subwoofer's passband of 39 – 110 Hz.

3.2 Large stage configuration

An identical analysis to what was performed on the small stage was carried out on the large stage data. The individual polar and frequency responses are shown in Figures 11 – 13, while the front-to-back rejection comparisons are given in Figure 14. Remember that the under stage subwoofer placement wasn't possible with this configuration due to stage height restrictions, so modelled data was used in lieu of measured data.

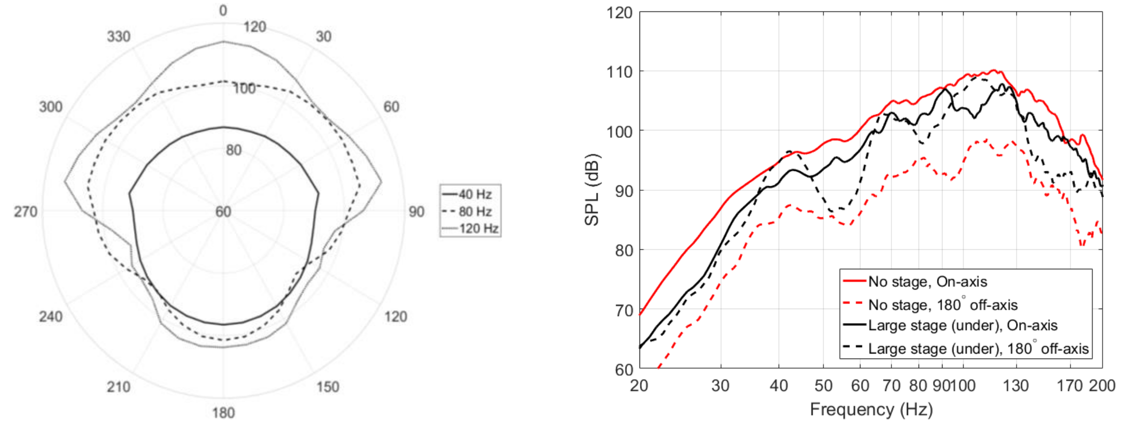


Figure 11 Modeled polar patterns (left) and frequency responses (right) of the d&b audiotechnik Y subwoofer in a non-anechoic environment, placed under a large stage

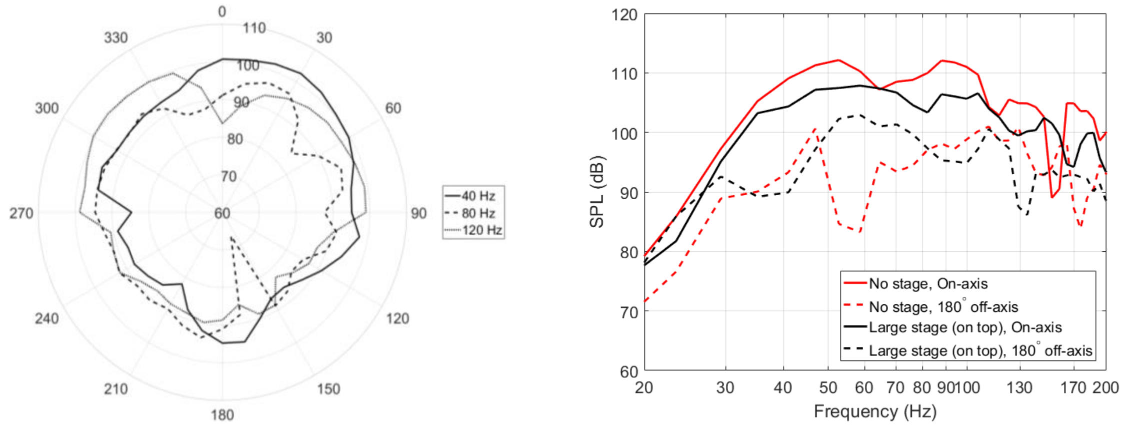


Figure 12 Measured polar patterns (left) and frequency responses (right) of the d&b audiotechnik Y subwoofer in a non-anechoic environment, placed on top of a large stage

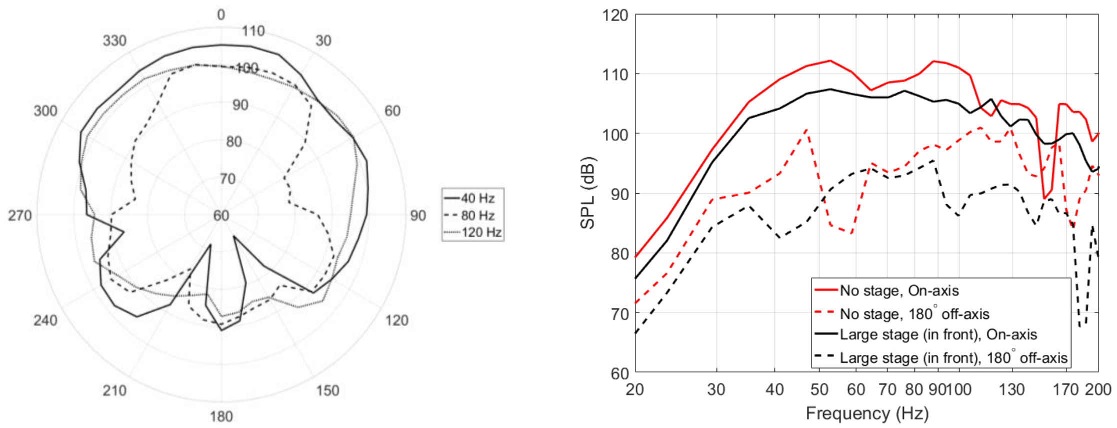
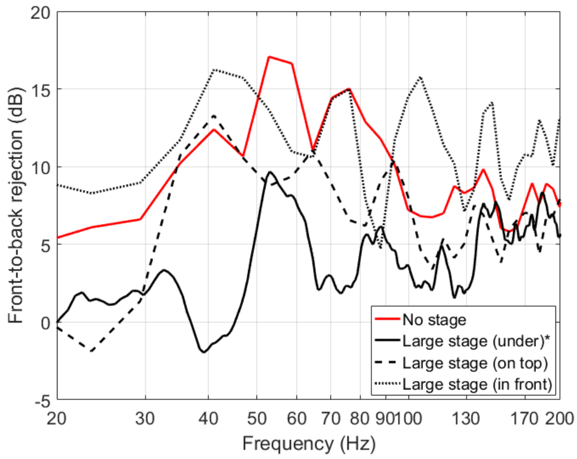


Figure 13 Measured polar patterns (left) and frequency responses (right) of the d&b audiotechnik Y subwoofer in a non-anechoic environment, just in front of a large stage



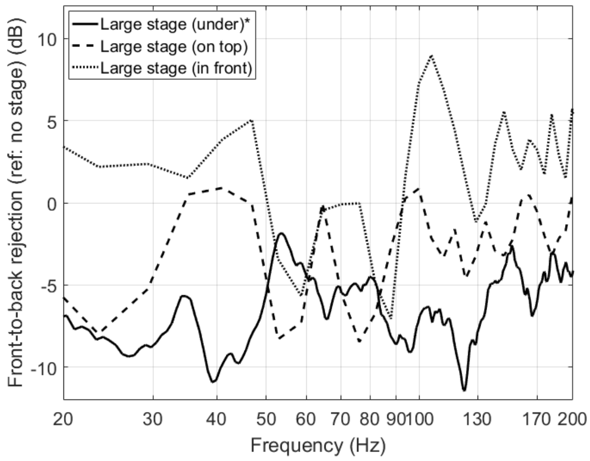


Figure 14 Comparision of front-to-back rejection for each subwoofer location (left = comparsion to stage-less configuation, right = deviation from the stage-less configuration, * modeled data)

There are some similar and some dissimilar trends when comparing the small and large stage configurations. The under stage subwoofer location appears to be the worst choice for both scenarios, although the data for the large stage was modeled, so further investigation is required. Interestingly, the front of stage subwoofer location struggles around 60 and 90 Hz, where it shows less front-to-back rejection than the subwoofer without a stage present.

A possible explanation is that the stage appears acoustically large in the subwoofer passband, meaning that most frequencies interact acoustically with it. Given that a wall was just behind the rear of the stage, a strong reflection may have interfered with the subwoofer polar response. The round trip propagation distance for this reflection to the subwoofer in front of the stage is 9.7 m. The frequency with a half-wavelength of 9.7 m is 17.68 Hz. Odd integer multiples of this will arrive at the subwoofer 180 degrees out of phase from the direct sound, causing cancellation of the front drive unit signal. In this case the key frequencies are 53 Hz and 89 Hz. For the secondary drive-unit, the propagation distance is 8.7 m, corresponding to potentially problematic frequencies of 59 Hz and 99 Hz. Whether this is a sufficient explanation for the loss of stage rejection for this configuration is a question that requires further research.

Finally, the mean front-to-back sound pressure level rejection over two frequency ranges, 39 – 110 Hz (subwoofer passband) and 20 – 300 Hz (wider range to take into account stage and room resonances), can be calculated for each configuration (Table 1) and related directly to the rejection achieved by the subwoofer on its own (Table 2).

Configuration	**Small stage**		**Large stage**	
	39 – 110 Hz	**20 – 300 Hz**	**39 – 110 Hz**	**20 – 300 Hz**
No stage	11.76 dB	9.37 dB	11.76 dB	9.37 dB
Under stage	6.32 dB	3.31 dB	3.91 dB*	5.11 dB*
On top of stage	5.36 dB	5.40 dB	8.48 dB	6.22 dB
In front of stage	13.10 dB	10.78 dB	12.67 dB	12.16 dB

Table 1 Mean front-to-back sound pressure level difference for each tested configuration
(* modelled data due to stage height restrictions)

Configuration	Small stage		Large stage	
	39 – 110 Hz	20 – 300 Hz	39 – 110 Hz	20 – 300 Hz
Under stage	-5.43 dB	-6.06 dB	-6.40 dB*	-5.63 dB*
On top of stage	-6.40 dB	-3.97 dB	-3.28 dB	-3.15 dB
In front of stage	1.34 dB	1.41 dB	0.92 dB	2.78 dB

Table 2 Mean front-to-back sound pressure level difference for each tested configuration (using the no stage configuration as a reference level) (* modelled data due to stage height restrictions)

The data shown in Tables 1 and 2 provide a clear and concise summary of the experimental findings. Placing a directional subwoofer underneath or on top of a stage (large or small) will significantly reduce the unit's front-to-rear sound pressure level rejection capability. Only placing the subwoofer in front of the stage will allow this rejection to be maintained.

4 CONCLUSIONS AND FUTURE WORK

The experimental results presented in this paper aid in furthering the understanding of the effect performance stage proximity has on a subwoofer's polar and frequency response. If a directional subwoofer is placed underneath or on top of a stage, there is a good chance that the unit's directivity will be partially or fully lost. This will result in unreasonably-high sound pressure levels on stage, thus placing performers and stage personnel at risk of excessive noise exposure as well as potentially creating an uncomfortable working environment. Placing a directional subwoofer in front of the stage by roughly one meter allows for the unit's directionality to be maintained. Based on the experimental results presented here and the modeled results presented in 2010 [5], the authors strongly recommend placing subwoofers in front of the stage over any other placement options.

Of course this analysis is largely meaningless should the system designer chose to suspend the subwoofer(s) above the stage. In this case, the polar pattern can be easily manipulated to avoid placing excessive energy on the stage through use of digital signal processing in the loudspeaker processing unit.

While this work presents some evidence demonstrating the potential impact a stage can have on subwoofer performance, there is more work required to fully understand the issue. The authors recommend the following additional research:

- Repeat the experiment, but in a hemi-anechoic space with a full stage, capable of up to two meters in height, to better represent a stage common to large-scale live events.
- Repeat the experiment, but in-situ at a large-scale live event (or a mock setup of one).
- Examine how systems consisting of multiple directional subwoofers and/or horizontal subwoofer arrays behave with different placement relative to a stage.
- Investigate any effects the stage has on a subwoofer system's transient response.

Although work is still required to fully understand the issue, it is clear that consideration must be made when placing ground-based subwoofers at live events, especially when low-frequency directivity is required. As most commercially-available software omits any stage effects from predications, it's essential to understand how a stage can affect the predicted response of a subwoofer and how to best configure systems so that the outcome is as close to the desired polar and frequency responses as possible.

5 REFERENCES

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